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Assessing the two plasmon decay instability in ignition-scale hohlraums

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Abstract

Assessing the $2\omega_{pe}$ instability and other preheat considerations in ignition-scale hohlraums

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In recent experiments[1] Sean Regan, *et. al.* for the first time observed the $2\omega_{pe}$ instability from window plasma in hohlraum targets. This instability can also operate[2] at peak power near the edge of the inner beams in the ablator plasma and near the edge of the outer beams in the liner plasma. Fortunately only a small fraction of the laser energy was estimated to be at risk. A more quantitative assessment of the energy at risk at peak power and its sensitivity to variations in target design and to details of the instability threshold model will here be given. We also explore how strong collisionality restricts this instability in the Au wall plasma. We show that the instability threshold can be significantly reduced for laser beams with an angle of incidence of about 60 degrees due to the swelling of the laser field near its turning point. A simple model is given. It is also shown that for frequently cited plasma conditions, the SRS-scattered light wave can itself drive the $2\omega_{pe}$ instability. This effect is relevant for the nonlinear saturation of SRS and the resulting heated electron generation. Some estimates are given. Finally several important issues concerning the high-energy electron distributions due to the $2\omega_{pe}$ instability and other laser plasma processes are discussed.

1. S. P. Regan et. al. (submitted to Phys. Rev. Letters)
2. W. L. Kruer. Paper Po6, 37th Anomalous Absorption Conference (2007)

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Summary

- Why look at the $2\omega_{pe}$ instability in ignition-scale hohlraums? (gradient and collisional thresholds/ intensity swelling for obliquely incident light/ hot electrons and preheat)
- Recent experimental feedback on the $2\omega_{pe}$ instability (direct drive experiments/ window hot electrons in hohlraums- S. Regan *et. al*.)
- The energy at risk to the $2\omega_{pe}$ instability at other times and places in hohlraums is being assessed.
- New nonlinear physics: sometimes the Raman-scattered light can excite the $2\omega_{pe}$ instability.
- Some preheat considerations: strong dependence on T_{hot}; energy distribution functions matter.

Why look at the $2\omega_{pe}$ instability?

The $2\omega_{pe}$ instability

- **often has the lowest intensity threshold**
  - **threshold even lower for overlapped beams**

- **produces high temperature electrons (T_{hot}~70keV)**
  - **hence preheat concern even for fabs<1%!**

- **can occur in window, ablator, and liner plasmas**
  - **for window plasma, see Sean Regan et. al.**
  - **effect can be enhanced in the ablator and liner plasmas with large beam spots**

- **is not included in the standard hohlraum lpi modeling**

The threshold intensity due to density gradients is rather low

- $$\left(\frac{v_{os}}{v_e}\right)^2 = \frac{12}{k_0 L} \approx 2.2\frac{\lambda_\mu}{L_\mu}$$
- $$I_{14} > \frac{59\theta_{keV}}{\lambda_\mu L_\mu}$$

Assuming normal incidence

Examples: Be T_{kev}=2.5 λ_μ=.35

- **L_μ=300 I>1.4x10^{14} W/cm^2**
- **L_μ=1000 I>4x10^{13} W/cm^2**

Note that the intensity can swell significantly for obliquely Incident light with angle of incidence ~ 60 degrees

Interesting question: how do speckles affect threshold?

Threshold intensity due to collisions is rather low in low Z material, rather high in Au.

Collisional threshold $\gamma_{\max} > \dfrac{\nu_{ei}}{2}$

Homogeneous plasma $\gamma_{\max}^{h} = \dfrac{\sqrt{3}}{8}\dfrac{v_{os}}{c}\omega_0$

Inhomogeneous plasma $\gamma_{\max} = \alpha\gamma_{\max}^{h}$ **α is a function of how far above gradient threshold one is**

$$I > \frac{1.4x10^9}{\alpha^2}\left(\frac{Z\ln\Gamma}{\theta_{keV}^{3/2}\lambda_\mu^2}\right)^2 \frac{W}{cm^2}$$

Examples; **ln=7 Z=4 (Be) T_{keV}=2.5 λ_μ=.35 α~1/3**
I> $5x10^{13}$ W/cm^2

ln=7 Z=50 (Au) T_{keV}=4 λ_μ=.35 α~1/3
I>$2x10^{15}$ W/cm^2

For angles of incidence ~60 degrees, the threshold intensity is significantly reduced by swelling of the incident intensity

- Simple example---linear density profile $n = n_{cr} z/L$
- obliquely incident light turns at $n = n_{cr}\cos^2\theta$
- $\varepsilon = \cos 2\theta - z/L$ and v_{gz} becomes small at the turning point and so E swells
- Airy function solution

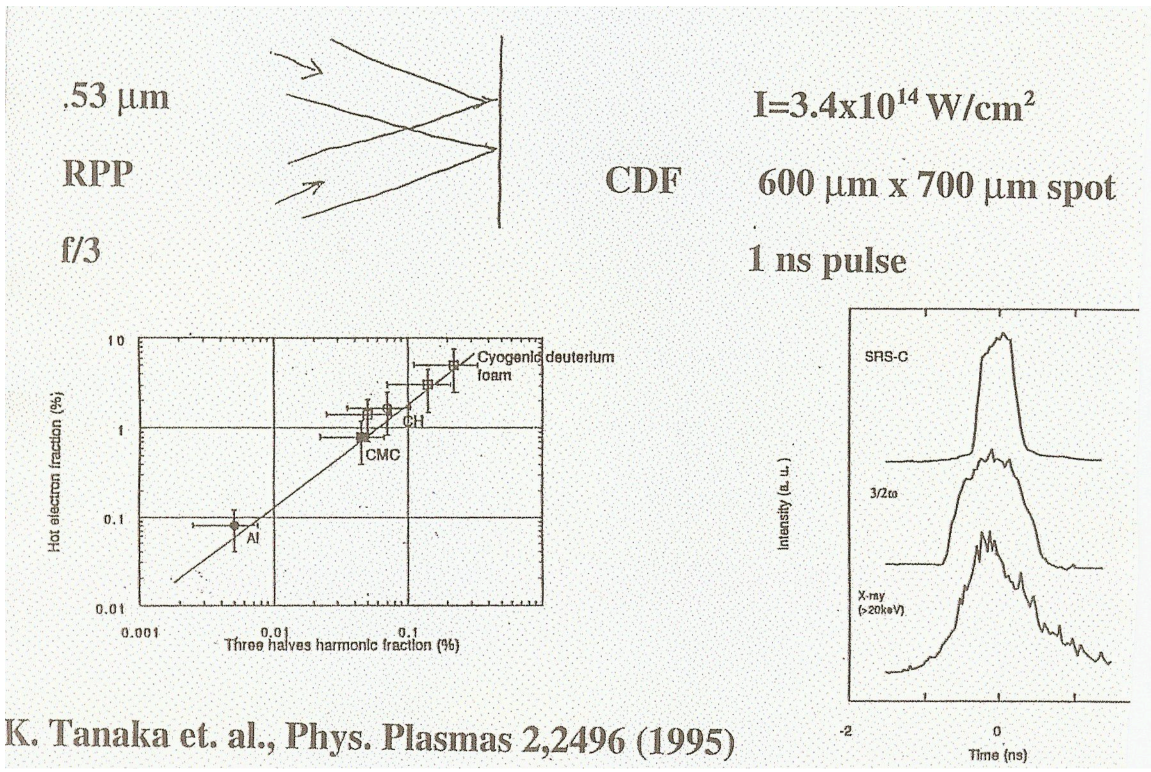
$$\frac{\partial^2 E}{\partial \eta^2} - \eta E = 0 \qquad \eta = \left(\frac{\omega^2 L}{c^2}\right)^{1/2} (z - L\cos^2\theta)$$

$$\left|\frac{E_{\max}}{E_{FS}}\right|^2 \approx 3.7\cos^2\theta\left(\frac{\omega L}{c}\right)^{1/3}$$

Typically $\left(\frac{\omega L}{c}\right)^{1/3} \geq 10$

The classic signature of the $2\omega_{pe}$ instability is $3\omega_0/2$ emission

Some Osaka experiments are illustrative



A better understanding of T_{hot} generated by the $2\omega_{pe}$ instability is needed

In recent experiments, T_{hot}~60-70 keV attributed to $2\omega_{pe}$ instability both in direct drive (LLE) and in hohlraum window plasmas (Regan, et. al.)

This T_{hot} is about what one might expect to be generated by the forward directed plasma wave in the hot plasma limit

Then $$T_{hot} \approx \frac{mv_p^2}{2} \approx 85keV$$

However, early (strongly driven) $2\omega_{pe}$ simulations suggested

$$T_{hot} \cong 110\left(\frac{I\lambda_\mu^2}{3x10^{15}}\right)^{.33} keV$$

Lasinsky,et.al., LLNL Annual Report 1980

For $I\lambda_\mu^2 \cong 10^{14} W/cm^2$ $\qquad T_{hot} \cong 35keV$

More understanding of the dependences of T_{hot} on intensity and T_{cold} is needed.

Summary

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- The energy at risk to the $2\omega_{pe}$ instability at other times and places in hohlraums is being assessed.

- New nonlinear physics: sometimes the Raman-scattered light can excite the $2\omega_{pe}$ instability.

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The $2\omega_{pe}$ instability continues to be a concern in direct drive experiments

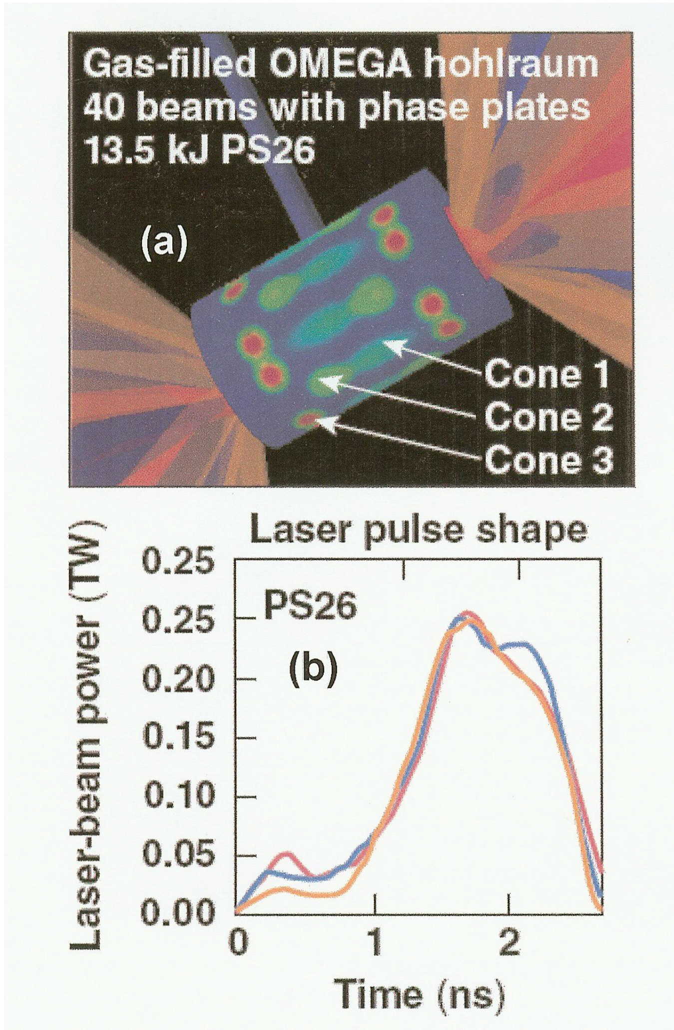
In recent “direct drive”experiments:

f_{abs}~1-15% into hot electrons with T_{hot}~60-70 keV
Is attributed to the $2\omega_{pe}$ instability
C. Stoeckl, et. al., PRL 90,235002-1, 2003

When above threshold in implosion experiments,
f_{abs}~15% is inferred to generate the preheat
if the hot electron transport is diffusive, f_{abs}~1-2%
if their transport is more directional (Delettrez)

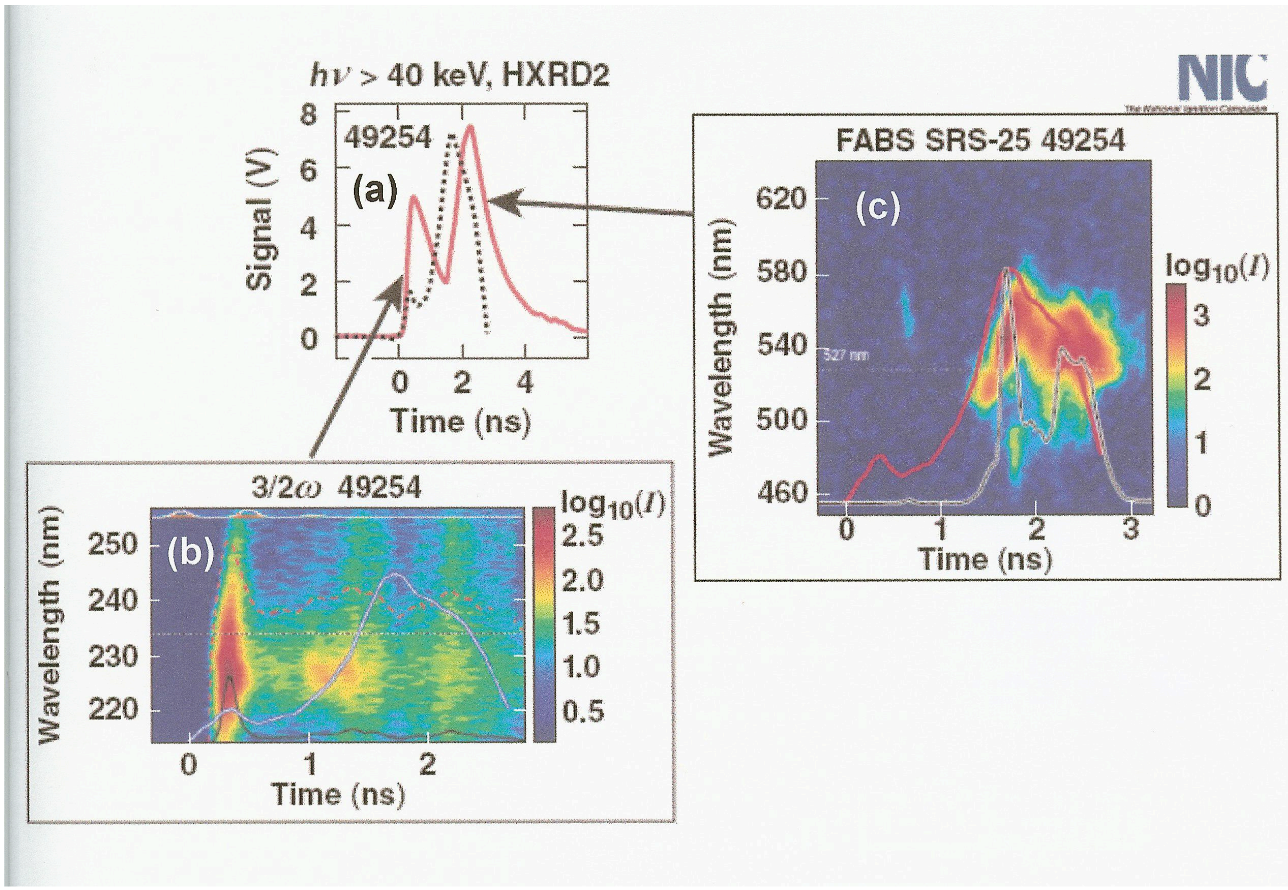
Note that net intensity is found to matter,
not single beam intensity

The $2\omega_{pe}$ instability was observed for the first time in hohlraums in Omega experiments (Regan, et. al.)



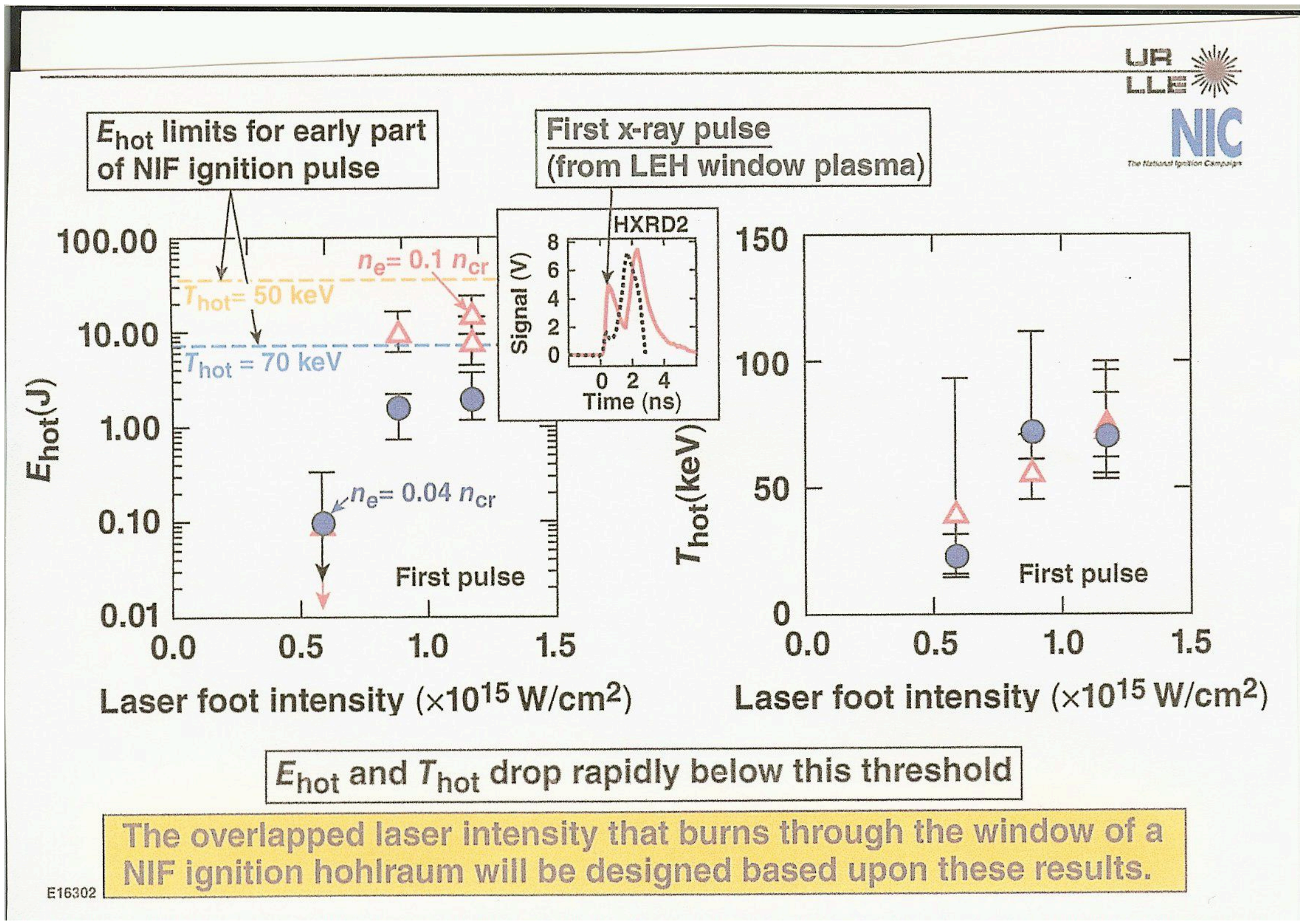
Sean Regan, et. al. submitted to PRL

Hot electron (T_{hot}~50+keV) generation was correlated with blow-up of the window and with 3/2 ω_0 emission.



S. Regan, et. al.

The hot electron temperature becomes ~70keV for the window hots



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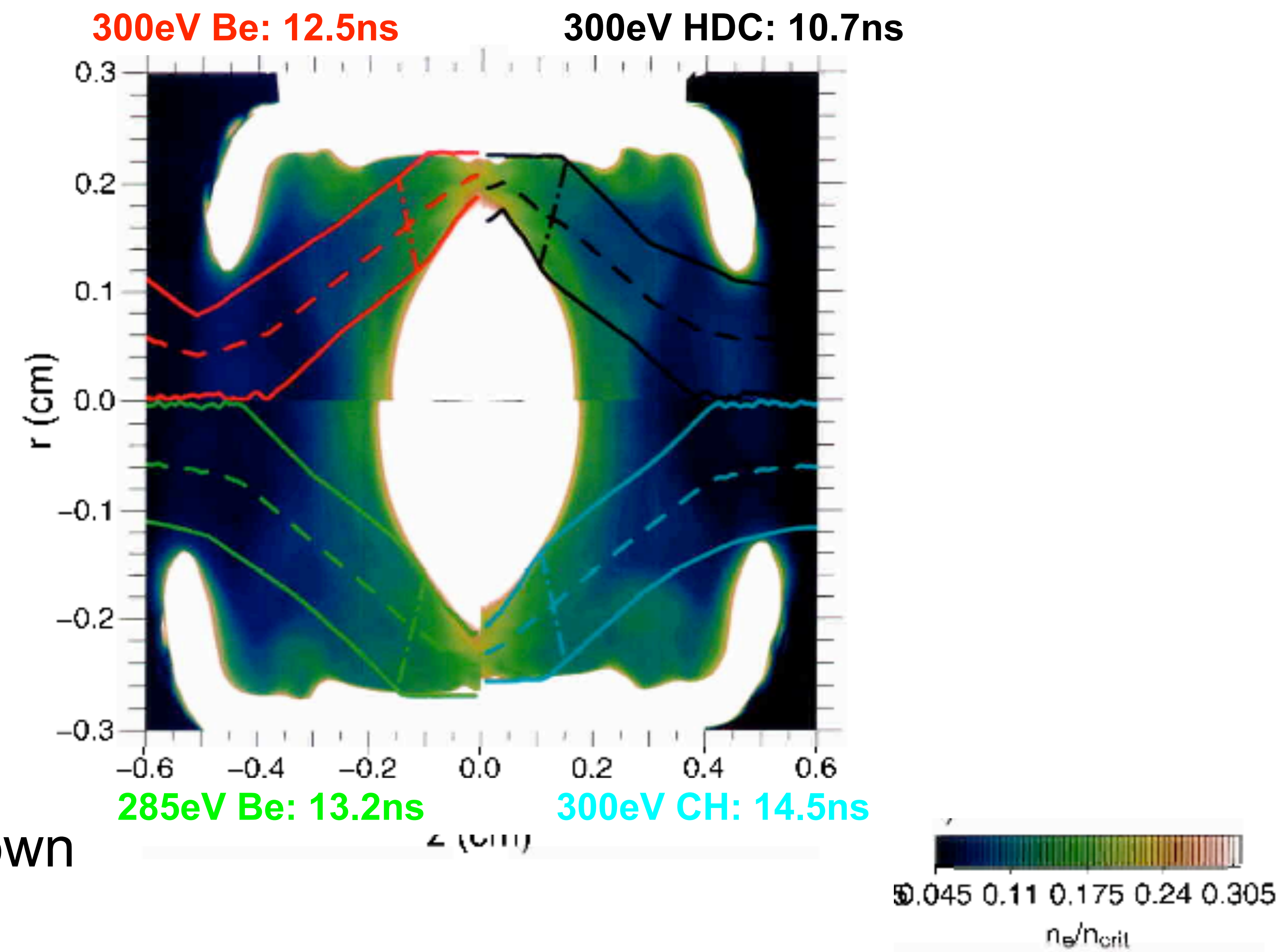
Portions of the inner beam skim plasma with density near quarter-critical density



Richard Town

We are now monitoring the “energy at risk” to the $2\omega_{pe}$ instability within the hohlraum

The energy at risk diagnostic

- **monitors laser energy striking quarter critical density with sufficient intensity to be above threshold for the $2\omega_{pe}$ instability**
- **was first developed to understand the window hots at early time**
- **the collisional threshold is now included**

Application to other times and places within the nominal NIF ignition hohlraum is underway by Nathan Meezan

Preliminary estimate for energy at risk in a recent point design: 4 kJ from inner cones.

Cone	E @ $n_c/4$ (kJ)	E @ risk (kJ)
23.5	15.4	3.3
30	25.5	0.7
44.5	76.1	0.0
50.	95.5	0.0

E @ risk is power at $n_c/4 \times (I\text{-}I_{thresh})/I$

$I_{thresh} = \max(I_{coll}, I_{grad})$

I_{coll} (10^{14})= 0.46 Z^2/T^3

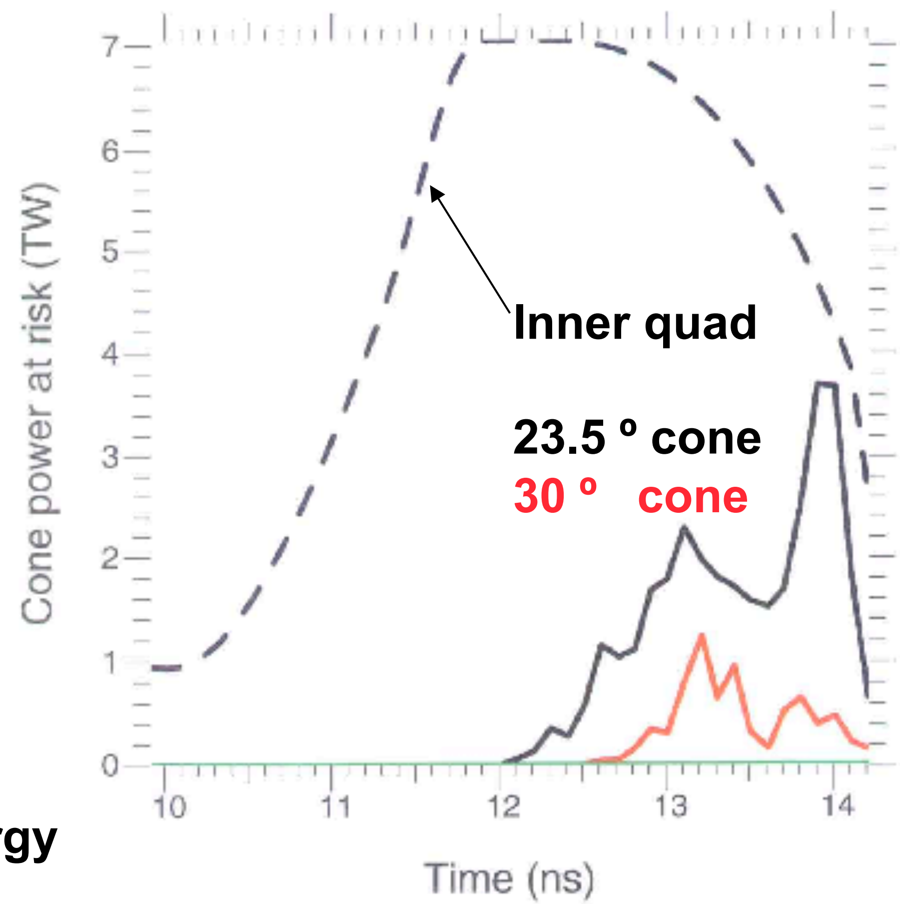
I_{grad} (10^{14})= 70.5*T/($L_{\mu m}$*0.351)

E @ risk is *laser* energy, not hot e- energy

If f_{abs}<10%, E_{hot}<400J

NIF hot e- spec @ peak ~ 6.4 kJ @ 70 keV

Power @ risk for NIF ignition design



Thresholds will be improved

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For common conditions accessed by the inner beams, the Raman-scattered light can excite the $2\omega_{pe}$ instability

• stimulated Raman backscatter at n/n_{cr}=.1 and T_e=2.5 keV

ω_{pe}/ω_0=.316 ω_s/ω_0=.633 $\omega_s \sim 2\omega_{pe}$!

At somewhat higher density, $\omega_s < 2\omega_{pe}$ but encounters $\omega_s \sim 2\omega_{pe}$ as the scattered light wave propagates to lower density plasma.

• Expect regime in which SRS becomes more absorptive, i.e., SRS-driven plasma waves makes hot electrons and the scattered light wave excites the $2\omega_{pe}$ instability, making even hotter electrons.

• Possible saturation mechanism for strongly-driven SRS

Excitation of the $2\omega_{pe}$ instability by the Raman-backscattered light

Consider previous example: n/n_{cr}=.1 T_e=2.5 keV $\omega_{sc}=.633\omega_0$

Assume $I_{sc}\sim.2I_0$ $I_0=5\text{x}10^{14}$ W/cm^2 $I_{sc}\sim10^{14}$ W/cm^2 (r~20%)

Threshold for excitation of the $2\omega_{pe}$ instability by the scattered light, noting that $\lambda_{sc}=.55\mu$m and taking $\alpha\sim1/3$

- **Gradient threshold (L=1mm)** $I_{TG}\sim2.5\text{x}10^{13}$ W/cm^2
- **Collisional Threshold (Be)** $I_{Tc}\sim2.5\text{x}10^{12}$ W/cm^2

Various consequences entail

- less Raman-scattered light measured but more hot electrons
- a higher temperature component (~70keV?)
- $3\omega/2$ emission at $\sim.95\omega_0$ (for this example)
- nonlinear reduction of level of SRS

$I_{sc} \sim I_{TG}$?   ($2\omega_{pe}$ instability probably not this efficient)

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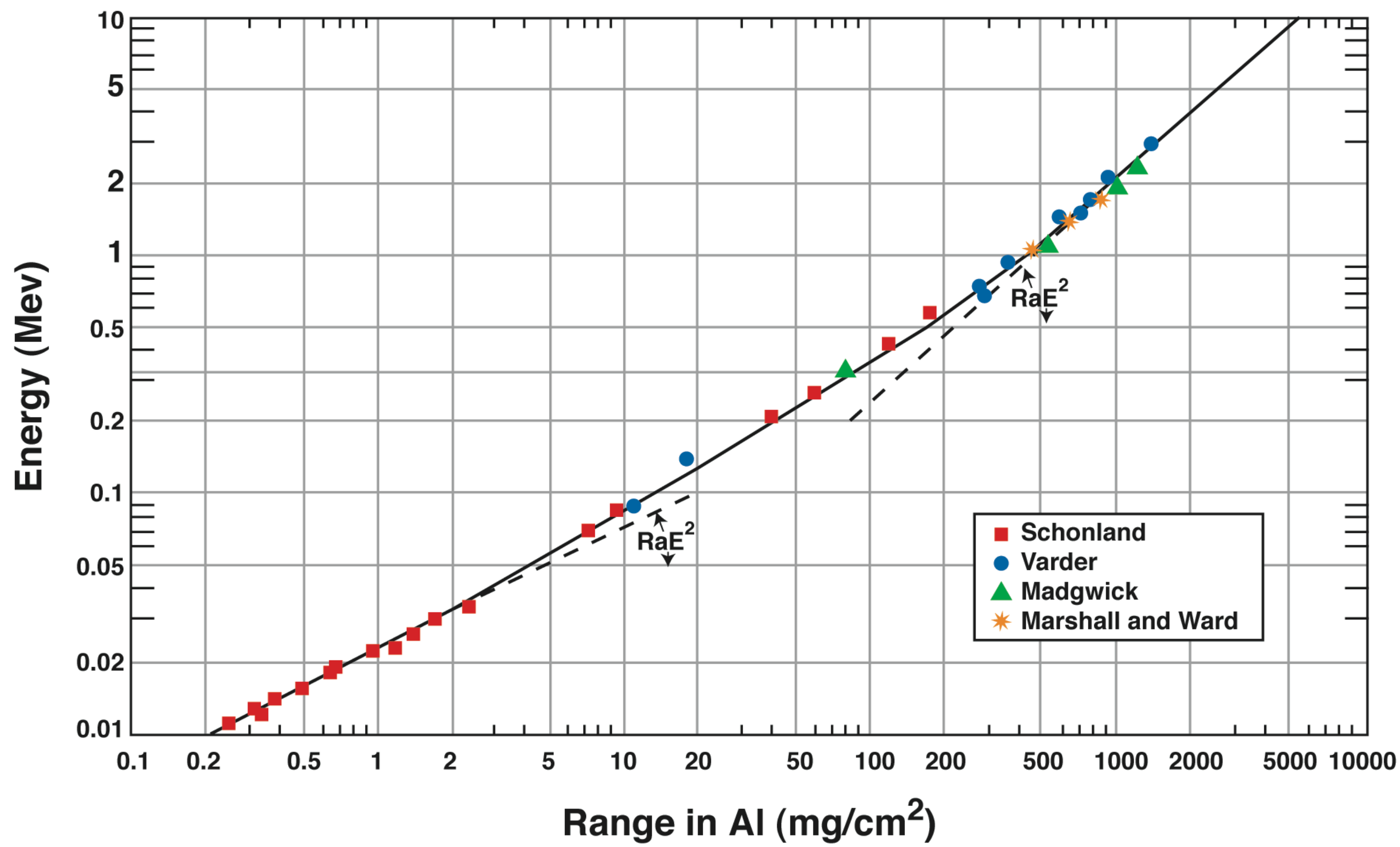
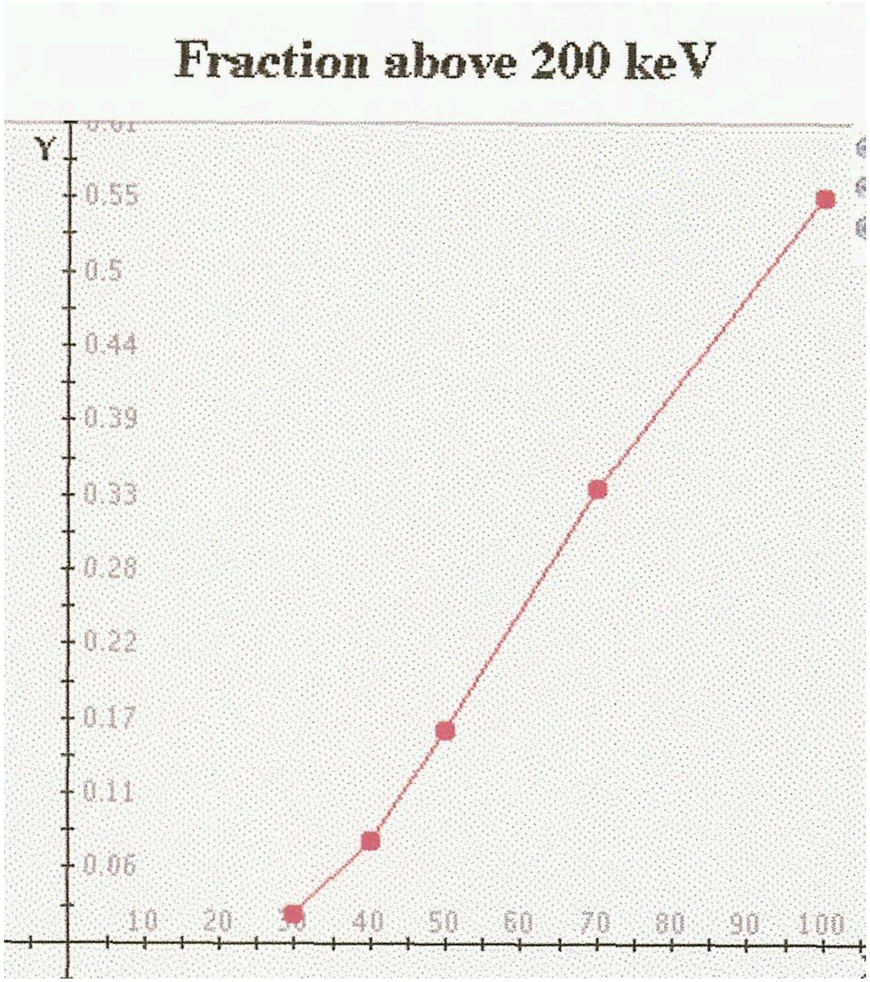
Only rather energetic electrons can penetrate the ablator of an ignition-scale capsule



Example: ρΔR~30 mg/cm2 ➔E> 200 keV

T_{hot} matters a lot!

fraction

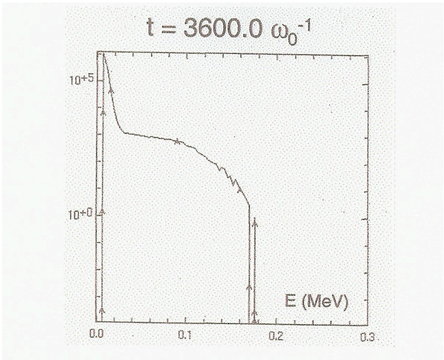


T_{hot}

Can the sensitivity of the preheat to T_{hot} be exploited?

- Win by finding ways to reduce T_{hot}
  for example, by inducing short wavelength ion fluctuations

- The most dangerous portion of the heated electron distribution may be under populated



PIC simulation of Raman backscatter
n/n_{cr}=.15, T_e=2 keV
Note that distribution diminishes at E>4-5T_{hot}
Wilks and Kruer (2005)

- Important that FFLEX have higher energy channels in order to be more sensitive to the electrons with energy >200 keV
  currently the highest energy channel is about 120 keV

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